

VU Research Portal

On the use of visual information in infant reaching actions

van Wermeskerken, M.M.

2012

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

van Wermeskerken, M. M. (2012). *On the use of visual information in infant reaching actions*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Chapter 2

The early development of the use of visual information for
movement control and perception

Published as:

van Wermeskerken, M., van der Kamp, J., & Savelsbergh, G.J.P. (2010). The early development of the use of visual information for action and perception. In D. Elliott & M. Khan (Eds.), *Vision and goal-directed movement: Neurobehavioral perspectives* (pp. 293-313). Champaign, IL: Human Kinetics.

Abstract

In adults, the human visual system is organized in two functional and neuro-anatomically dissociated visual systems; a system involved in online movement control and a system involved in perception, that is, obtaining knowledge about objects, events, and places (Milner & Goodale, 1995, 2008). On a behavioral level these systems can be distinguished based on the visual information that they preferably exploit and the time scale at which they operate. Whereas movement control mainly exploits egocentric (i.e., viewpoint-dependent) sources of information, which is short lived, perception primarily is reliant on allocentric (i.e., viewpoint-independent) sources of information, which can be retained over longer time intervals. In the current review it is investigated whether this dissociation between movement control and perception already exists in early infancy. Indeed, findings suggest different developmental trajectories for movement control and perception with respect to their reliance on visual information. That is, whereas 1- to 3-month-old infants' control of visual tracking and reaching primarily is reliant on egocentric information, their perception of motion velocity and motion direction chiefly relies on allocentric information around 1 month of age. The development of the interaction between the two processes, as suggested by research using the occlusion paradigm, does not seem to develop before 4 months of age. Hence, it is tentatively concluded that the use of visual information for movement control and visual perception is dissociated shortly after birth.

Introduction

At the age of 3 months, infants can already intercept slowly moving objects (van Hof, van der Kamp, & Savelsbergh, 2002, 2006, 2008; von Hofsten, 1980, 1983; von Hofsten & Lindhagen, 1979). Obviously, these infants are not yet proficient reachers, but their reaching quickly becomes more sophisticated between 6 and 12 months of age. For example, 6-month-old infants reach and look toward the future interception position of a moving object rather than reach and look to its present position. This is particularly evident when the object suddenly stops moving or changes direction. In these cases, 6-month-old infants reach toward the original future location of the object (von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998). Findings such as these provide clear evidence that, from 6 months on, infants are able to anticipate the spatiotemporal properties of moving objects. Intriguingly, however, habituation experiments with visual events similar to those in this reaching study show that it is not until the age of 8 months that infants perceive the future position of a moving object when they are not reaching for it (Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994).

These findings suggest that the development of movement control and the development of perception are not necessarily intrinsically linked. Each may follow its own temporal trajectory. The relationship between movement control and perceptual development has been the subject of several theories (e.g., Atkinson, 2000; Bertenthal, 1996; Netelenbos, 2000; Piaget, 1952). It has been assumed, for instance, that the development of movement control precedes the development of perception (e.g., Piaget, 1952; see also Held, 1965). Though the findings discussed earlier do not exclude such a view, further empirical findings do question this claim. After all, research has indicated that infants have rather refined perceptual abilities at birth or shortly thereafter (Atkinson, 2000; Gopnik & Meltzoff, 1996; Kellman & Arterberry, 1998; Rochat, 2001).

Thus, a reconsideration of the relationship between the development of movement control and the development of perception is needed. The working hypothesis of this chapter is that the development of movement control and development of perception are not necessarily related, at least as far as the exploitation of visual information is concerned. We consider neither movement control nor perception as privileged in development. The theoretical framework of the present chapter is formed by the work of Gibson (1979/1986) and Milner and Goodale (1995, 2008). Gibson, the founder of the ecological approach to perception and action, argued that perception results from

the direct pickup of visual information—that is, to perceive is to detect meaningful information that specifies the to-be-perceived or to-be-acted-upon environmental property. From this perspective, development is a process of convergence to more useful information.

Following a great deal of neuropsychological work, Milner and Goodale (1995, 2008) suggested that there are two independent but interacting visual systems: one for visual control of movements and one for visual perception of the environment (i.e., obtaining knowledge about the environment). According to Milner and Goodale, these two visual systems are functionally and anatomically separate. Therefore, it is appropriate to distinguish between the use of visual information for movement control and the use of visual information for perception, as well as to distinguish between the timescales at which the systems operate. In this chapter, we explore the consequences of this theoretical framework for the relationship between the development of movement control and the development of perception.

In the next sections, we elucidate the perspectives of Gibson and then Milner and Goodale in more detail, resulting in the proposition that the development of movement control and perception may not be necessarily related. Unfortunately, empirical work that directly tests this contention is scarce and often circumstantial. However, we will review literature on the early development of movement control and perception that suggests that the early development of eye and arm movements for moving objects and the visual perception of motion direction and velocity of moving stimuli follow distinct trajectories. We then review the development of the control of eye and arm movements in situations in which the object is temporarily out of sight in order to explore how the interaction between movement control and perception processes may develop in the first year of life.

Ecological approach to perception

Gibson (1979/1986) introduced the ecological approach in psychology. His approach broke with the traditional view that the ambiguous retinal image forms the starting point for visual perception (Reed, 1996). This approach held that visual perception is the formation of an internal representation of the world by transforming, encoding, or decoding the sensory stimuli that impinge on the retina. Gibson rejected the idea that perception is such a process of enrichment. Rather than beginning with the retinal image, Gibson took the optic array as the starting point for visual perception.

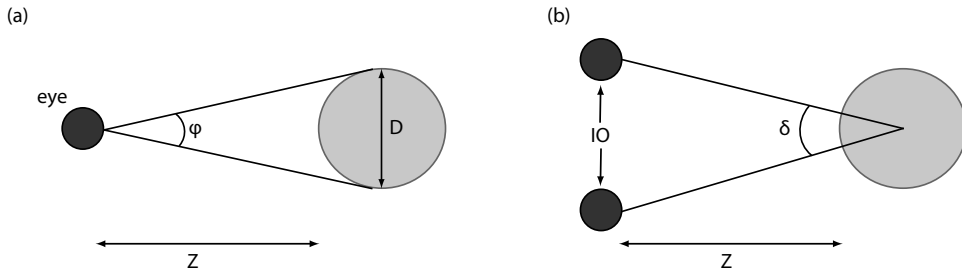


Figure 2.1 A ball with diameter (D) approaching at distance (Z) from the perceiver's eye(s). **(a)** Representation of monocular viewing. The angle subtended between the eye and the ball is the optic angle (φ), which is a function of the ball's diameter (D) and distance (Z). The available monocular variables are the optic angle (φ); its derivative ($\dot{\varphi}$), which is the rate of change of the optic angle (φ); and $\tau(\varphi)$, which is the inverse of the rate of change of optic angle (φ). Whereas the variables (φ) and ($\dot{\varphi}$) are affected by object size, $\tau(\varphi)$ is not. **(b)** Representation of binocular viewing. The angle subtended between the eyes and the ball is (δ), which is a function of the interocular separation (IO) and the distance (Z). The available binocular variables are the optic angle (δ); its derivative ($\dot{\delta}$), which is the rate of change of optic angle (δ); and $\tau(\delta)$, which is the inverse of the relative rate of change of the optic angle (δ). None of these variables is affected by object size.

The optic array comprises a pattern of light coming from all directions of the environment to a single point of observation. It is structured and consists of optical patterns that are specific and as such are lawfully related to objects, events, and places. Consider, for instance, an infant looking at an approaching ball (Figure 2.1). As the distance between the infant's head and the approaching ball diminishes, the optic array encompasses an expansion pattern that specifies the time remaining until the object reaches the infant, or tau, which is expressed as $\tau(\varphi)$ and is the inverse of the relative rate of optical expansion of the angle subtended by the ball (Lee, 1976). In other words, there is a one-to-one mapping between optical information and environmental properties, making enrichment processes redundant. The detected information is meaningful in itself. Gibson referred to this process of picking up information as *visual perception*.

The empirical agenda of the ecological approach is to identify the visual informational variables that specify objects, events, and places for perception and for the guidance of movements (Gibson & Pick, 2000). Again, the infant looking at a moving ball can serve as an example. Suppose the infant tries to grasp or hit the approaching ball. The infant needs visual information that specifies, for example, when to start reaching for the ball. Figure 2.1a illustrates the situation. The optical angle

(φ), the angle subtended by the edges of the ball and the infant's eye, increases with the approach of the ball. The infant might use this variable and initiate the catching movement whenever the optical angle reaches a critical value. In the case where the diameter of the ball (D) is constant, optical angle (φ) specifies the distance between the ball and the eye.

However, for objects with different or unknown diameters, the information that this variable provides is ambiguous. In that case, it would be better to use the inverse of the relative rate of change of the optical angle, or tau ($\tau(\varphi)$; Figure 2.1). Tau specifies the time until the ball reaches the eye, provided the ball approaches with constant velocity. Since tau is independent of ball diameter, it provides information about time or distance across a broader range of objects and events. An infant who exploits this variable would be better adapted to the task compared with an infant who relies on the optic angle (φ). By coupling the more useful optical variables to movement variables, movements are guided more efficiently. Hence, movement and information are directly coupled with each other, and inferential processes are superfluous.

One important task for the newborn, then, is to attune to the more useful optical variables to obtain knowledge about the environment and to guide movements (van der Kamp, Oudejans, & Savelsbergh, 2003). This process of attunement was demonstrated by van Hof and colleagues (2006), who presented 2- to 8-month-old infants with moving balls of varying sizes under monocular and binocular viewing conditions. Because the use of any binocular information (e.g., δ or $\tau(\delta)$; see Figure 2.1b) is independent of ball diameter, reliance on this type of information yields better performance across a larger range of objects than reliance on monocular information only (e.g., φ) yields; the timing of a catching movement is independent of ball size under binocular but not monocular viewing (van der Kamp, Savelsbergh, & Smeets, 1997).

It was therefore hypothesized that infants capable of exploiting binocular visual information should tune their movements independent of ball size under binocular viewing. By contrast, infants relying only on monocular information should show timing patterns affected by ball size under both binocular and monocular viewing. By means of a cross-sectional and longitudinal experimental design, van Hof and colleagues (2006) demonstrated that with increasing age, infants came to rely more on binocular information. More specifically, from the age of 5 months onward, the initiation of the reaching movements became increasingly independent of ball size

under binocular viewing but not under monocular viewing. In contrast, among the 3- to 4-month-old infants, the timing of the reaching movements was affected by the size of the approaching ball irrespective of the viewing condition, indicating that these infants used monocular information. Similar findings of attunement to more useful information with increasing age were also provided by Kaye and van der Meer (2000, 2007) for defensive blinking and by van Hof and colleagues (2008; Savelsbergh, Caljouw, van Hof, & van der Kamp, 2007; van Hof, 2005) for intercepting moving balls.

Evidence for the process of convergence can also be found in studies of infant visual perception (e.g., Johnson, 2004; Johnson et al., 2003b; Sitskoorn & Smitsman, 1995). These studies are typically concerned with whether infants perceive possible and impossible events in accordance with certain laws (e.g., law of inertia, law of continuity) by means of preferential looking or habituation methods (Sitskoorn & Smitsman, 1995; Spelke et al., 1994; Wattam-Bell, 1996a, 1996b). They indicate that with age, infants exploit visual information that specifies properties of objects or events across a larger range of experimental conditions.

Thus far, we have only superficially touched upon the distinction between the use of visual information for online control of movements and the use of visual information for perception. This distinction between movement control and perception is not imposed by the ecological approach (Michaels, 2000). However, neuropsychological evidence, to be discussed shortly, suggests that such a distinction between the two processes exists. In the next section, we elaborate on the distinction between the use of visual information for movement control and the use of visual information for perception. We then explore the consequences of this distinction for development.

Two visual systems

Goodale and Milner (1992, 2004b; Milner & Goodale, 1995, 2008) claim that there are two structurally and behaviorally distinct visual systems. One is involved in the visual control of movements, whereas the other is concerned with the visual perception of objects, events, and places. The dorsal stream, which projects from V1 to the posterior and superior parietal cortex, is thought to support movement control. The ventral stream, on the other hand, supports perception and projects from V1 to the inferior temporal cortex. This distinction of the use of visual information in movement control and perception is derived from observations of patients with neuropsychological deficits (see Carey, 2010). Patients with visual agnosia (i.e., with

damage to the ventral stream) are unable to accurately perceive object shape, size, and orientation but nevertheless are able to appropriately guide movements to these objects.

One of the most frequently studied patients is D.F., whose ventral system was damaged by carbon monoxide poisoning. D.F. shows good performance (i.e., at a level comparable to participants without neurological deficits) on a posting task in which a handheld card is inserted into a slot set to various orientations (Goodale et al., 1994; Goodale, Milner, Jakobson, & Carey, 1991). By contrast, D.F.'s performance deteriorates dramatically when she has to match the orientation of the card to the slot without inserting it in the slot. Conversely, patients with optic ataxia (i.e., with damage to the dorsal stream) are able to recognize objects and use information about size, shape, and orientation to describe them. However, these patients are not capable of using this information to control movements. They perform poorly in the posting task but are able to perceptually distinguish among the slot orientations (Perenin & Vighetto, 1983, 1988; see Milner & Goodale, 1995).

A similar phenomenon is observed in children with Williams syndrome (WS), a rare genetic condition that is associated with deficits of the dorsal stream (Atkinson, 2000; Atkinson et al., 1997). In line with observations of patients with optic ataxia, children with WS encounter difficulties when performing the posting task but not when matching the orientation of the card to that of the slot. In addition, these children fail to smoothly perform a movement; instead, they perform a sequence of small movements that are continuously controlled visually (Atkinson et al., 1997, 2003, 2006; Elliott, Welsh, Lyons, Hansen, & Wu, 2006). Taken together, these patient studies show that there are perception and movement control tasks that involve distinct visual processes related to ventral and dorsal stream functioning.

Before we further elucidate the differences between the use of visual information for movement control and the use of visual information for perception, we should emphasize that Milner and Goodale's view of visual perception and the visual guidance of movement control stands in sharp contrast to the ecological approach (Michaels, 2000; van der Kamp & Savelsbergh, 2000, 2002). For example, Milner and Goodale defined visual perception as a process that "allows one to assign meaning and significance to external objects and events" (Milner & Goodale, 1995, p. 2) and as the "creation of an internal model or percept of the external world . . . a model that can be used in the recognition of objects and understanding their interactions" (Goodale

& Humphrey, 1998, pp. 206-207). According to Milner and Goodale, the two visual systems differ in the way visual stimuli are transformed or encoded. Perception and movement control require different transformations of the same visual stimulus; the stimulus is encoded into allocentric or egocentric frames of references, respectively.

In contrast, proponents of the ecological approach refute the necessity for these enrichment processes. They explain the difference between movement control and perception in terms of distinct sources of visual information that are picked up and used (Michaels, 2000; van der Kamp, 1999; van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008; van der Kamp, Savelsbergh, & Rosengren, 2001). In this view, movement control and perception differ in their reliance on egocentric (body-centered, viewer-dependent) information and allocentric (world-centered, viewer-independent) sources of information. The visual control of goal-directed movements primarily relies on egocentric sources of information. By contrast, visual perception is chiefly based on allocentric sources of information that specify objects, events, and places relative to each other. These latter sources of information are thought to result in perceptual illusions (see Westwood, 2010). The Ebbinghaus illusion, for instance, consists of a circle surrounded by smaller or larger circles (see Figure 2.2). When the outer circles are smaller than the inner circle, the inner circle is perceived to be larger than it is. Conversely, the inner circle is perceived to be smaller when it is surrounded by larger circles. However, if the inner circle is grasped, hand aperture is scaled to the real size of the circle and not to the perceived size. Thus, visual perception takes the visual context into account, but the visual control of movements remains largely unaffected (Aglioti, DeSouza, & Goodale, 1995; van Doorn, van der Kamp, & Savelsbergh, 2007).

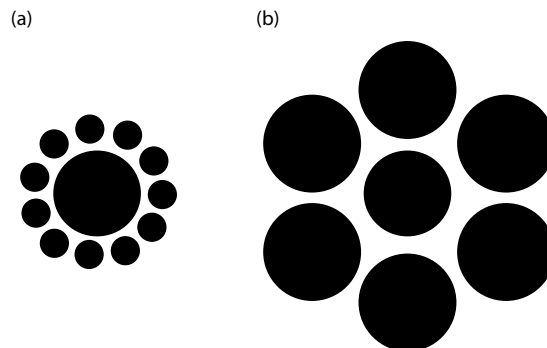


Figure 2.2 The Ebbinghaus illusion. **(a)** A circle surrounded by smaller circles makes the inner circle appear larger. **(b)** A circle surrounded by larger circles makes the inner circle appear smaller.

Besides relying on different sources of visual information, movement control and perception are also distinguished by the timescale at which they operate. Movement control entails the pickup of information to instantaneously control the ongoing movement. The information is used online (i.e., immediately) and decays quickly thereafter—it is short lived. In contrast, visual perception does not involve a time constraint—visual information used to obtain knowledge about the environment can be exploited over longer time intervals.

These differences in timescale can be shown by introducing a temporal delay between information pickup and movement execution. Due to the quick decay of the information, a delay results in perturbation of the online movement control processes. It appears that under these circumstances, movement control becomes more reliant on allocentric sources of information, resulting in specific changes in the kinematics of the movement (e.g., Hu, Eagleson, & Goodale, 1999). For example, a delay causes a perceptual illusion (i.e., allocentric information) to affect movement execution (e.g., Mendoza, Hansen, Glazebrook, Keetch, & Elliott, 2005; Westwood, Chapman, & Roy, 2000; Westwood & Goodale, 2003; Westwood, McEachern, & Roy, 2001). These findings indicate that not only the use of visual information for movement control and perception entails different timescales but also the two processes complement each other. If one process is compromised, the contribution of the other may increase.

In sum, there is good evidence that the use of visual information for movement control and perception is dissociated. Movement control and perception rely on different sources of information and operate at different timescales. However, even though these processes are separate, they work together and may serve complementary functions. Consequently, it is not appropriate to make the distinction between movement control and perception based on the exploitation of egocentric versus allocentric sources of information absolute. Indeed, whether to make the distinction at all is currently under debate (Mendoza et al., 2005; Milner & Goodale, 2008; see also Rossetti & Pisella, 2002). Handlovsky, Hansen, Lee, and Elliott (2004), for instance, found that the Ebbinghaus illusion (see Figure 2.2) affects online movement control. In their study, the presence and absence of illusory stimuli (i.e., allocentric information) before and during movement execution were manipulated independently. Participants were presented with a circle that was (1) not surrounded by circles, (2) surrounded by smaller circles (see Figure 2.2a), or (3) surrounded by larger circles (see Figure 2.2b). During aiming movements toward the inner circle, the display remained the

same or changed by eliminating the surrounding circles (in the cases that stimulus 2 or 3 was displayed) or by adding small or large surrounding circles (in the case that stimulus 1 was presented). When a surround of small circles was added, the time the participants needed to perform their aiming movement decreased significantly. This reduction was attributed to a decrease in time between peak velocity and termination of the movement, a portion of the movement that is associated with online control (Handlovsky et al., 2004; see Mendoza et al., 2005). The other manipulations, however, did not result in significant differences in movement time. Nevertheless, the findings suggest that the online visual control of movement does not exclusively rely on egocentric information; allocentric information may be exploited as well. It is possible to argue, therefore, that distinguishing between movement control and perception based on egocentric and allocentric information is inappropriate (e.g., Mendoza et al., 2005; Smeets & Brenner, 1995). However, considering other sources of evidence, we think that the distinction is still tenable (and valuable) if it is kept in mind that the distinction is not absolute.

Development of the use of visual information for movement control and perception in infancy

In the previous section, we discussed the distinction between using visual information for movement control and using it for perception. We argued that there are two independent but interacting visual systems, one concerning the visual control of goal-directed movements and the other dealing with obtaining knowledge about the environment. The distinction between the uses of visual information in adults raises the issue of the early development of these two processes, as well as their interaction.

In the remaining sections of this chapter, we explore these developmental issues. First, we focus on the findings of earlier studies that suggest separate developmental trajectories for movement control and perception. We do this by assessing the involvement of egocentric and allocentric information in infants' movement control and perception processes. Second, we evaluate whether movement control and perception operate at different timescales (online versus off-line) in early development. More precisely, we discuss studies that suggest an interaction between the two processes early in infancy.

Early development of movement control

For adults, it has been demonstrated that the visual control of movements is primarily guided by egocentric information, whereas allocentric information seems of lesser importance. We explore whether this is also true during the first year of life, examining whether goal-directed movements that manifest during early development (i.e., eye movements and reaching) are more reliant on egocentric information than on allocentric information.

Eye movements

Research on tracking visual stimuli indicates that infants use egocentric information to control eye movements. Von Hofsten and Rosander (1996, 1997; Rosander & von Hofsten, 2000, 2002) have examined infants' ability to track moving objects under various conditions, including manipulations of egocentric and allocentric sources of information. These researchers investigated 1- to 3-month-old infants who were tracking a target that oscillated in front of them. The target was so big that it covered the entire field of view so that there was no background information (von Hofsten & Rosander, 1996). The authors found that infants as young as 1 month are able to track the moving target and that tracking performance improves substantially with age. The lag with which infants tracked the target was smaller for older versus younger infants. The authors argued that this decrease in temporal lag was due to an improved ability to couple eye movements with head movements both spatially and temporally. The findings suggest the use of egocentric sources of information. Specifically, the movements of head and eyes are controlled based on information that specifies the movement of the target relative to the infant. This conclusion was based on the fact that, because of the size of the target, there was no background that could provide additional information about the position of the target. In effect, allocentric information was eliminated.

The same results were found for tracking smaller objects that moved relative to a homogeneous background, which also fails to provide additional allocentric information about the target position (Rosander & von Hofsten, 2002; von Hofsten & Rosander, 1997). Tracking performances in 1-to 5-month-old infants were similar. However, when the small object moved in front of a patterned background (i.e., allocentric information), tracking was facilitated only in infants aged 3 months and older (Rosander & von Hofsten, 2000). Von Hofsten and Rosander argued that the

background provided additional information (i.e., allocentric information) that served as a reference frame to guide eye movements at the turning points. Consequently, it might be concluded that, until 3 months, infants rely solely on egocentric information to control eye and head movements when tracking a moving object. Infants at that age do not appear to benefit from additional allocentric sources of information; however, allocentric information seems to improve tracking performance beyond that age.

Further evidence suggesting that young infants rely on egocentric sources of information to control eye movements is provided by Gilmore and Johnson (1997, 1998). In their studies, they presented 4- to 6-month-old infants with a visual stimulus on a central monitor located in front of the infants followed by a sequence of two brief visual stimuli that flashed first 30° to the left of the center of fixation and then 30° to the right of the center of fixation (see Figure 2.3a). The flashes occurred before the infants shifted gaze. The infants had to integrate the positions of both flashes to accurately fixate them. The authors argued that if an infant relies on information relative to the eye position (what they denote a *retinocentric reference frame*)¹, then the infant would not be able to fixate both stimuli sequentially; the second saccade would fall short (see Figure 2.3b). More specifically, picking up information specifying the location of both target stimuli relative to the current eye position prevents the information from being veridical across eye movements. That is, when an eye movement (e.g., gaze shift) is made to the first target, the exploited information of the second target location remains specific to the former eye position but not to the new eye position. By contrast, picking up information combining the retinal and eye position (i.e., a *head-centered reference frame*) would result in fixating both target stimuli, since this information remains veridical across eye movements as long as the head does not move.

It was found that 6-month-old infants were capable of making accurate eye movements to both stimuli, suggesting that they detected information about the locations of the flashed stimuli relative to their head position. Infants who were 4 and 5 months old, however, did not succeed in guiding eye movements to the second target; they made errors that were consistent with the use of retinocentric sources of information. Importantly, all infants relied primarily on egocentric sources of information to control eye movements; the exploited information specified a relationship between the infant and the visual stimuli. However, Gilmore and Johnson

¹ The term reference frame, also used by Milner and Goodale (1995), is equivalent to *sources of information* (i.e., retinocentric sources of information).

(1997, 1998) did not specifically aim at disentangling egocentric and allocentric sources of information. Consequently, similar results would have been obtained when the older infants had used allocentric information, because with a stable head position (relative to the environment), head-centered egocentric and background allocentric sources of information covary. Nevertheless, the youngest infants did clearly rely on retinocentered egocentric information.

These findings strongly suggest that during early development, infants' eye movements primarily rely on egocentric information. There is no evidence that infants before the age of 3 months exploit allocentric sources of information. Yet, beyond this age allocentric information may add to the accuracy of eye movements. The evidence, however, is partly circumstantial because direct tests, for instance by manipulating egocentric and allocentric information, are lacking.

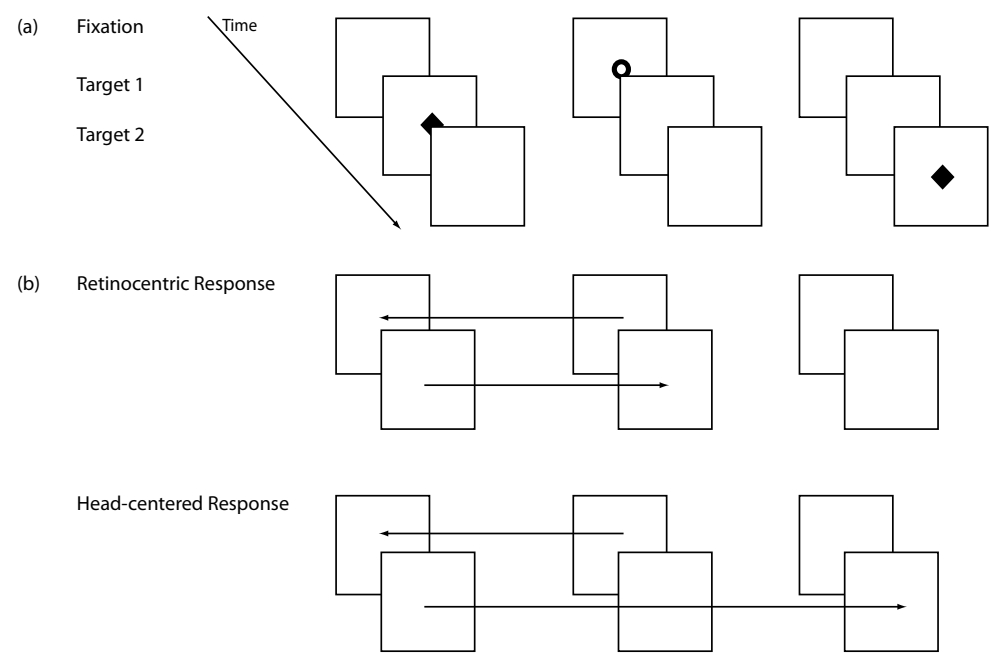


Figure 2.3 A pictorial summary of the main conditions of Gilmore and Johnson's (1997) experiment. **(a)** Display sequence of the visual stimuli. After fixation of the first stimulus, two stimuli were flashed on the right or the left monitor, one after the other. **(b)** Response types in accordance with the exploited egocentric information (i.e., retinocentric or head centered).

Reaching

In a similar vein, infants were found to primarily exploit egocentric information when reaching for moving objects. As mentioned earlier, by 3 months of age, infants are already capable of intercepting moving objects. Of course, this does not by itself imply that infants use egocentric information. After all, they might gain knowledge about where to move the hand in space relative to a location in the environment rather than relative to the self. For example, a ball that moves on a set trajectory (as is usually the case in infant studies) can be intercepted at a fixed location relative to some feature in the environment. However, von Hofsten (1980, 1983; von Hofsten & Lindhagen, 1979) argued that infants' reaching toward objects that approach on a fixed trajectory from different directions (from the left and right of the baby) with different velocities (3.4-30 cm/s) are guided by egocentric information. He argues that "the infant reaches in reference to a coordinate system fixed to the moving object instead of to the static background" (von Hofsten, 1983, pp. 83-84). In other words, infants extrapolate the future position of the moving ball and control their reaching accordingly (von Hofsten, 1980, 1983; von Hofsten et al., 1998). Infants' reaching behavior is not characterized by stereotyped reaching toward a fixed position relative to other objects in the environment; rather, it seems to be adapted to the approach characteristics relative to the self. This indicates use of egocentric information when controlling reaching movements.

The use of egocentric information while reaching for a moving object is also consistent with the findings of van Hof (2005; see also van Hof et al., 2008). She revealed that 3- to 9-month-old infants who reach for moving objects approaching frontally at different speeds (10-200 cm/s) detect and use visual information specifying the temporal relationship between the infant and the object (i.e., egocentric information). Moreover, older infants exploited more useful egocentric information to guide their reaching movements than the younger infants; 3- to 5-month-old infants timed their reaching based on the optical angle (φ). Recall that this variable is defined as the angle subtended by the edges of the ball and the infant's eye (see Figure 2.1). Thus, the optic angle is an egocentric (head-centered) source of information. Reliance on this variable yields initiation of the reach when the object is at a fixed distance from the observation point. The older infants, in contrast, used the absolute rate of change of the optical angle ($\dot{\varphi}$) or tau ($\tau(\varphi)$). As a result, these infants timed their reaching movements based on time rather than distance. This strategy is more sophisticated. It yields better

performance because a distance strategy causes the infant to initiate the reaching too late in the case of high ball velocities. Either way, these findings suggest that infants use egocentric information when controlling reaching movements toward moving objects.

The results are consistent with the use of egocentric information, but they are not definite because none of the studies involved the manipulation of allocentric information. Fortunately, there is a series of studies that provide insight into the reliance on allocentric sources of information (Clifton, Muir, Ashmead, & Clarkson, 1993; Clifton, Rochat, Robin, & Berthier, 1994; McCarty & Ashmead, 1999; McCarty, Clifton, Ashmead, Lee, & Goubet, 2001; Robin, Berthier, & Clifton, 1996). Robin and colleagues (1996), for instance, presented 5- and 7.5-month-old infants with moving and stationary objects in two illumination conditions (light and dark). In the dark condition, a glowing object was presented in an otherwise dark environment. Consequently, the infants could pick up only egocentric information; all sources of allocentric information were eliminated.

In accordance with earlier research of Clifton and colleagues (Clifton et al., 1993, 1994), the study found that infants' reaching behavior toward stationary objects was comparable for both illumination conditions. The authors argued that sight of the hand does not affect the reaching, an observation that is compatible with findings concerning reaching in adults (e.g., Elliott, 1990). Importantly, the observation that reaches remained unperturbed also indicates that infants at this age do not rely on allocentric sources of information when controlling their arm movements. In addition, the authors reported that when presented with moving objects, infants showed fewer reaches in the dark condition than in the light condition (Robin et al., 1996), but once they attempted to reach for the ball, they performed at a level comparable to that of the light condition. The latter finding suggests that elimination of allocentric information may make it more difficult for infants to perceive what the environment offers for action (i.e., affordance perception; Gibson, 1979/1986). Yet, the use of vision to control the movement was not affected by the presence or absence of allocentric information.

In sum, the evidence on the use of egocentric and allocentric information in movement control during early development is largely circumstantial. That said, these studies indicate that during early development, the control of eye and arm movements is primarily guided by egocentric information. Furthermore, the studies suggest that only at later ages does allocentric information come into play, with egocentric information still being the most pertinent source in movement control.

Early development of visual perception

Having considered the empirical evidence for the use of egocentric (and allocentric) information in the early development of movement control, we now describe the use of visual information in the early development of perception. In adults, visual perception is thought to rely on allocentric rather than egocentric information (Milner & Goodale, 1995). In this section, we assess whether this is also true for the early development of visual perception. To allow for comparison with the findings on movement control in the previous section, we restrict ourselves to perception of speed and direction of motion of moving stimuli.

Infant perception is commonly investigated using habituation or preferential looking methods (e.g., Dannemiller & Freedland, 1989, 1991; Kaufmann, Stucki, & Kaufmann-Hayoz, 1985; Mason, Braddick, & Wattam-Bell, 2003; Wattam-Bell, 1991, 1992, 1996a, 1996b). In preference-looking experiments, an infant is presented with two visual stimuli simultaneously. By measuring the infant's looking time for each stimulus, it is determined whether the infant has a preference for one of the stimuli. In that case, it is assumed that the infant visually discriminates the stimuli. In habituation experiments, an infant is repeatedly shown the same stimulus. Habituation occurs when the infant loses interest in the stimulus, indicated by a significant decrease in looking time. If a new stimulus elicits longer looking times, dishabituation is said to occur. Once again, the inference is that the infant visually discriminates the two stimuli. (Note that these methods do not entail the assessment of how infants control eye and head movements when they look at the visual stimuli. The researcher's interest is only in the duration of looking as an indicator of what infants perceive.)

To date, the contributions of allocentric and egocentric information sources in the early development of the perception of motion direction and velocity have received scant attention. Identification of their contributions would entail independent manipulation of the two. Given the difficulties involved in manipulating egocentric sources (e.g., moving the baby in synchrony with the moving object), the manipulation of allocentric information may be more fruitful. It is predicted that eliminating allocentric sources of information (e.g., by presenting the stimulus in an entirely darkened environment or on a screen that encompasses the infant's entire field of view) would have profoundly adverse effects on the perception of motion direction and motion velocity early in development.

Perception of motion velocity

Infants who are 1 month perceive motion velocity when presented with a stimulus that moves relative to a static environment (e.g., the boundaries of a monitor), although this ability is restricted to a narrow range of velocities that expands with age (Dannemiller & Freedland, 1989, 1991; Kaufmann et al., 1985; Volkman & Dobson, 1976; Wattam-Bell, 1992). Infants who were 6 weeks old detected differences in velocity of 9°/s (Aslin & Shea, 1990), whereas infants who were 20 weeks old were able to perceive much smaller differences in velocities of 2.3°/s to 1.2°/s (Bertenthal & Bradbury, 1992; Dannemiller & Freedland, 1989). Unfortunately, these studies do not provide insight into the contributions of allocentric and egocentric information. These sources of information always covaried because they were not independently manipulated. Hence, further research is needed to discover whether infants primarily rely on allocentric sources of information for the perception of motion velocity.

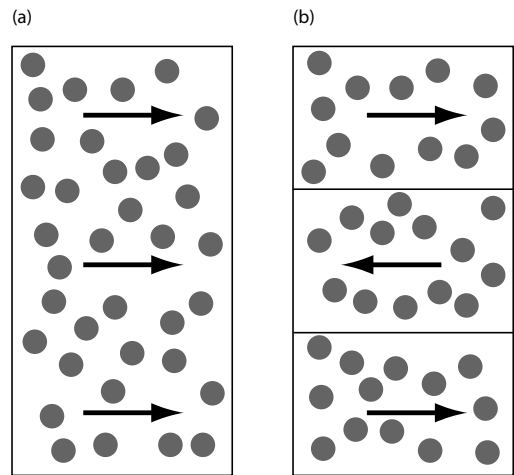


Figure 2.4 Typical display used in studies employing random-dot stimuli to investigate the perception of motion direction in infants. **(a)** Uniform display: All dots move uniform and coherently (as shown by the arrows). **(b)** Segregated display: In the upper and lower box of the display, the dots move uniformly, whereas the dots in the middle box move in the opposite direction (as illustrated by the arrows in the boxes).

Perception of motion direction

Infants’ perception of motion direction has been studied in more detail. Wattam-Bell (1992, 1994, 1996a, 1996b) examined 1- to 4-month-old infants’ ability to perceptually discriminate stimulus displays. Infants’ looking behavior for displays

with a static stimulus pattern and displays with a coherently moving uniform stimulus pattern were compared, or infants' looking behavior for displays with a coherently moving uniform stimulus pattern was contrasted with looking behavior for displays with segregated stimulus patterns moving in opposite directions (see Figure 2.4).

These studies revealed that 1-month-old infants discriminated between the static and moving stimulus patterns. However, it was not until the age of 7 to 8 weeks that infants discriminated between the uniform and segregated stimulus patterns. In other words, although 1-month-old infants could perceive motion *per se*, it took at least 2 weeks more before they were able to perceive the direction of motion (Atkinson & Braddick, 2003; Wattam-Bell, 1992, 1994, 1996a, 1996b; see also Dannemiller & Freedland, 1989, 1991). Banton, Dobkins, and Bertenthal (2001), who used similar segregated stimulus patterns but with motion directions that ranged between 0° and 180° , found that the ability to detect differences in motion direction improved with age. For the 6-week-old infants, no threshold could be obtained. Consistent with the findings of Wattam-Bell, even the opposite motions (i.e., 180°) were not discriminated by these infants. By 12 weeks, however, infants discriminated a difference in motion direction of 22° , whereas the 18-week-old infants were able to discriminate differences of 17° .

In addition to presenting egocentric information (i.e., motion direction of the stimulus pattern relative to the stationary infant), these studies also presented allocentric information about motion direction. This information was directly available from the segregated stimulus patterns within a display. These studies therefore cannot elucidate infants' reliance on egocentric versus allocentric information. However, Wattam-Bell (1996a, 1996c) conducted several habituation experiments that do speak to the issue. He used coherent and uniform motion displays in which allocentric information was not always present. In the first study (Wattam-Bell, 1996a, experiment 3), infants aged between 3 and 8 weeks were habituated to a display that either contained uniform rightward motion or uniform leftward motion. In the subsequent test phase, infants were presented with a display that contained both uniform motion directions. Wattam-Bell (1996a) reported that the infants did not discriminate between the original and the new motion direction. Rather than providing allocentric information within a display (as in the segregated displays shown in Figure 2.4), this experiment allowed infants to extract allocentric information about motion direction only by comparing two displays. It might have been these differences in the sources of allocentric

information that prevented the 6- to 8-week-old infants from discriminating motion direction when looking at two displays that contained opposite but uniform stimulus patterns (Wattam-Bell, 1996a). In contrast, infants of the same age discriminated motion direction when they looked at segregated stimulus patterns (Wattam-Bell, 1996a, 1996b).

More convincing evidence that these young infants rely on allocentric sources of information comes from an experiment in which infants were habituated to upward and downward motion (Wattam-Bell, 1996c, in Atkinson, 2000, and in Braddick, Atkinson, & Wattam-Bell, 2003). In the subsequent test phase, the infants were presented with only the opposite motion direction. Moreover, care was taken to eliminate all sources of allocentric information. No motion boundaries or alternative sources of background information were available (Atkinson, 2000, pp. 80-81; see also Braddick et al., 2003). In other words, the only information available on motion direction during the habituation and test phases of this experiment was relative to the infant (i.e., egocentric). Wattam-Bell found that infants did not dishabituate before the age of 12 weeks. Therefore, the ability to perceive absolute motion direction using only egocentric information does not appear to emerge before the age of 12 weeks. By contrast, perceptions of motion direction occur between 6 and 12 weeks when allocentric sources of information are available.

To conclude, although the evidence is scarce and incomplete, it seems that allocentric sources of information are much more important than egocentric sources in the development of visual perception. Infants younger than 3 months seem completely reliant on allocentric information for the perception of motion direction. By contrast, egocentric information contributes only after 3 months of age.

Interaction between movement control and perception processes in early infancy

Up to this point, we have considered the early development of visual information usage in movement control and perception of the environment separately. The present review suggests that egocentric sources of information play a major role in the early development of movement control, whereas allocentric sources of information appear central in the early development of perception. This suggests that movement control and perception follow separate developmental trajectories. Yet, adult studies have shown that the two separate processes work together and may serve complementary functions. Recall that a temporal delay between the detection of information and

movement execution can have profound influences on movement kinematics (Hu et al., 1999). The temporal delay perturbs the dorsal online movement control processes, which results in the engagement of ventral perception processes in movement control. This ventral contribution is demonstrated by the presence of an illusion bias in the movement kinematics (e.g., Westwood et al., 2000, 2001). The present section assesses the development of this interaction during infancy. If the use of visual information in movement control and perception is separate shortly after birth and follows different trajectories (Atkinson, 2000; Bertenthal, 1996; Rochat, 2001; van der Kamp & Savelsbergh, 2000, 2002; von Hofsten et al., 1998), what does this mean for the interaction between the two processes? Is the interaction already present at birth, or does it emerge later, and does it need further development? To explore these issues, we discuss studies in which infants tracked or reached for objects. These are movements that, under normal circumstances, are guided by egocentric information. In these studies, however, a temporal delay was introduced by either darkening the room and target or by placing a screen between the moving object and the infant.

Effects of temporal delay on infants' reaching and tracking

Clifton and coworkers demonstrated that 4-month-old infants presented with a stationary sounding object in the dark are able to touch and grasp the object (Clifton et al., 1993; Clifton, Perris, & Bullinger, 1991; see also Bower & Wishart, 1972). This is at approximately the same age as the first successful reaching for objects in the light and could be interpreted as a well-developed interaction. Specifically, the ventral perception system is capable of taking over the control of reaching.

However, at least two observations qualify this claim. First, during these experiments the lights were turned off shortly after the reach was initiated. The reason for this procedure was that otherwise the infants did not reach (Clifton et al., 1991; see also Hood & Willats, 1986). In other words, it seems that 4-month-old infants do not reach, or reach less frequently, for objects when a temporal delay is introduced. Second, even the reaching movements that were initiated when the room was darkened were less accurate and had kinematic characteristics that were substantially different from reaching for objects in the light (Clifton et al., 1993; Clifton et al., 1991). The reaches in the dark had higher velocities and were of shorter duration compared with reaches in the light (McCarty & Ashmead, 1999). Temporal delays in adults, however, commonly result in lower velocities and longer durations (Hu et al., 1999). The reason

for the opposite effects between infants and adults is unclear. It might be related to the auditory information available from the sounding objects in the infant studies. The findings, thus, are not unambiguous, but they do suggest that young infants are less likely to reach when a temporal delay is introduced.

Research that used moving objects is less ambiguous. These studies introduced a temporal delay between the pickup of information and movement execution by using a brief blackout (i.e., total darkening of the environment and moving target) or occlusion (i.e., placing a screen between the infant and the path of motion of the object). These studies revealed that infants before 4 months of age do not track, and infants before 5 months of age do not reach for objects that move temporally out of sight. It is only beyond these ages that infants perform predictive tracking and reaching movements under these circumstances (Jonsson & von Hofsten, 2003; Munakata, Jonsson, Spelke, & von Hofsten, 1996; Rosander & von Hofsten, 2004; van der Meer, van der Weel, & Lee, 1994; von Hofsten, Kochukhova, & Rosander, 2007). Recall that predictive tracking and reaching without temporal delays emerges at 1 and 3 or 4 months of age, respectively. Clearly, infants initially are not capable of dealing with the perturbations to the online control process caused by a temporal delay. It seems to take at least 1 month more before they start to compensate for these perturbations. It is likely that this ability reflects the first interaction between movement control and perception processes.

The way that 4-month-old infants perform predictive tracking differs for situations in which the object is or is not temporally out of sight—that is, infants' tracking over an occluder is saccadic rather than smooth (Rosander & von Hofsten, 2004; von Hofsten, 2004; von Hofsten et al., 2007), and the head lags the moving target to a larger extent during the occlusion and blackout conditions than in a full-vision condition (Jonsson & von Hofsten, 2003). Furthermore, until 5 months of age, infants do not reach when the trajectory of a moving object is partially occluded (van der Meer et al., 1994). Beyond that age, infants increasingly reach for the occluded ball, though the amount of reaching is less frequent compared with full-vision conditions (Jonsson & von Hofsten, 2003). Van der Meer and colleagues (1994) also reported that 5- to 8-month-old infants initiated their reach at a fixed location (i.e., relative to the screen), whereas older infants started their reach at a certain time before the ball reappeared. More kinematic data are not available from these studies.

Taken together, the findings indicate that, as in adults, the introduction of a

temporal delay between information pickup and movement execution perturbs infants' control of tracking and reaching. In the youngest infants, predictive tracking and reaching broke down, suggesting that no other processes (including those involved in perception) could compensate for the perturbation of the movement control system. It follows that the movement control and perception processes do not work together in the beginning. Nonetheless, from 4 months (in the case of tracking) to 5 months (in the case of reaching), infants seem able to guide their movements when the object is briefly out of sight. Because the kinematic characteristics of these movements are distinct from situations in which the object is not occluded from sight, it might be that ventral perceptual processes contribute. Support for the latter contention would be provided if it could be shown that predictive tracking and reaching for objects that are temporarily out of sight involve allocentric information. We explore this issue in the next section by comparing the findings from blackout and occlusion studies.

Comparison between blackout and occlusion studies

The information sources that are available to control predictive tracking and reaching in the blackout and occlusion studies differ. In the blackout studies, where both the environment and target are completely darkened, all visual information is eliminated. By contrast, in the occlusion studies, where a screen is placed between the moving object and the infant, only the egocentric sources are eliminated; several allocentric sources remain. For instance, the borders of the occluding screen provide information about where the moving object disappears and reappears. If infants' successful predictive tracking and reaching for objects that are temporarily out of sight is supported by ventral perceptual processes, it would be expected that infants would perform better in the occlusion situations than in the blackout situations because the former provides allocentric sources of information. Indeed, tracking performance is more proficient in occlusion situations versus blackout situations (Jonsson & von Hofsten, 2003; Munakata et al., 1996). Infants frequently stopped tracking the moment the object disappeared and then shifted their gaze to the other edge of the screen to where the object would reappear. Sometimes, infants were observed to shift their gaze to the far edge of the screen where the object would reappear, return to the edge of the screen where the object disappeared, and make a final gaze shift back to the location of reappearance (Rosander & von Hofsten, 2004; von Hofsten et al., 2007). It thus seems that infants exploit information from the screen to predict where

the object will reappear and use that information to guide their eye movements. In the blackout situation, this information was not available, resulting in less predictive tracking. Tracking movements in the blackout situation were slower, which resulted in lags larger than those observed in occlusion situations (Jonsson & von Hofsten, 2003; Munakata et al., 1996).

It is somewhat surprising that reaching performance deteriorates more in occlusion versus blackout situations (Jonsson & von Hofsten, 2003). This finding is not what would be expected. Instead of inhibiting predictive reaching, allocentric information sources in the occlusion situations should have facilitated it. Two explanations come to mind. First, it might be that our hypothesis that the ability of 5-month-old infants to successfully reach for moving objects that are temporarily out of sight points to the contribution of ventral perceptual processes simply is incorrect. Alternatively, the screen might absorb the infants' visual attention after the object disappears behind it (Jonsson & von Hofsten, 2003; Rosander & von Hofsten, 2004; von Hofsten, 2004; von Hofsten et al., 2007).

In conclusion, the evidence suggests that interaction between movement control and perception processes develops within the first year of life. It is not until about 1 month of age after infants can successfully track and reach for objects that they can deal with a temporal delay between the detection of visual information and movement execution. With respect to tracking, certain circumstantial evidence suggests the involvement of allocentric information sources in overcoming the temporal delay. However, much more experimental work is needed to substantiate this claim.

Conclusions and future directions

In this chapter, we explored whether the early development of visual information usage for perception and of visual information usage for movement control follow separate developmental trajectories. Following the neuropsychological work of Milner and Goodale (1995) and Gibson's ecological approach to perception and action (Gibson, 1979/1986), we argued that the use of visual information for perception and the use of visual information in movement control differ in the type of information that is exploited for the processes as well as in the timescale at which the two processes operate. Movement control processes primarily but not exclusively involve the instantaneous use of egocentric sources of information, whereas visual perception is much more reliant on allocentric sources of information that are available over longer

amounts of time. Importantly, the two processes must interact to achieve successful performance. If, for example, the movement control processes are perturbed, the contribution of the perception processes in performance is likely to increase.

A selective review of the development of visual information usage in movement control and perception suggests different developmental trajectories. On the one hand, the control of tracking and reaching movements for objects moving in different directions and with different speeds primarily relies on egocentric information between 1 month (in the case of tracking) and 3 months (in the case of reaching) after birth. It appears that allocentric information does not contribute before 3 months of age, at least as far as it concerns tracking. The role of allocentric information in reaching is less clear, although reaching in the dark for glowing objects suggests that until 7 months of age, allocentric information plays a minor role at best. On the other hand, the perception of motion direction, which emerges about 6 weeks after birth, chiefly relies on allocentric information. There is tentative evidence that egocentric information sources do not get involved before 3 months of age. In other words, on a developmental timescale there may be a differential involvement of egocentric and allocentric information sources. If true, this would lend support to the idea that the separation between the use of visual information in movement control and the use of visual information in perception already exists shortly after birth. However, caution is warranted since much of the evidence that we presented is circumstantial and needs further testing.

The same is true for the empirical evidence related to the development of the interaction between the two processes. Research suggests that until the age of 4 months (in the case of tracking) to 5 months (in the case of reaching), a temporal delay between the detection of the information and movement onset leads to a breakdown of movement control. It is only beyond these ages that infants learn to deal with this type of perturbation. One hypothesis is that this is due to the visual perception system becoming engaged in the control of movements. Hence, the first indications of interaction between movement control and perception processes would occur between 4 and 5 months of age, depending on the task. At this stage of research, this interpretation is rather speculative, and alternative explanations cannot be ruled out.

Clearly, the first round of research should be directed at substantiating the claims we have made here. However, if we speculate that they are at least partly true, then a second round of research will have to deal much more explicitly with the relationship

between the development of movement control and the development of perception. As mentioned early in the chapter, several theories posit that the development of movement control precedes the development of perception, but there are equally strong claims to the contrary (e.g., Atkinson, 2000; Kellman & Arterberry, 1998; Piaget, 1952). We have argued that neither movement control nor perception is privileged in development but that each follows its own developmental trajectory. This does not mean that movement control and perception develop in total isolation. On the contrary, we are convinced that they mutually influence each other. Van Hof and colleagues (2008), for example, showed in 3- to 9-month-old infants that improvements in the perception of whether a moving object can be caught are related to the infant's proficiency in controlling the catching movements, suggesting that the development of perception is constrained by the development of movement control. It is for future research to unravel exactly how and when the development of movement control and the development of perception influence each other.

